BEAM DYNAMICS SIMULATION IN DTL WITH RF QUADRUPOLE FOCUSING

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Abstract

There are a number of ion linear accelerators using RF focusing. Radio Frequency Quadrupole (RFQ) is the most useful RF linac in low energy range due to good focusing capability and well known design. Using of RFQ at medium energies is impractical because of low energy gain rate. Therefore, it was proposed to combine Drift Tube Linac (DTL), keeping tolerable energy gain rate, and RFQ. Such linac consists of a periodic sequence of a several number of drift tubes and RF quadrupole electrodes, located in the same Interdigital H-type (IH) resonator. Some different variants of this structure are considered. The beam dynamics simulation is carried out through the linac. The main parameters of the linac are determined. The RF model design, providing combination of DTL and RFQ, is proposed.

INTRODUCTION

The requirements of low particle losses and high currents of accelerating ion beams gets RFQ linacs more useful as an initial section of the linac. However the rate of energy gain of the conventional RFQ reduces very fast. It constitutes 0.5 – 0.7 of IH-DTL energy gain at $\beta = 0.05$. Thus using of the conventional RFQ at medium energies ($\beta > 0.07$) is impractical.

IH-DTL linac has several good performances at medium energies. It provides high energy gain, high shunt impedance and small tank diameter. The main problem in design of medium energy sections of the linac is the transverse beam focusing. The focusing by using of the quadrupole magnetic fields or axisymmetric RF fields (for example alternating phase focusing) are the most useful focusing types. Some of promising methods is Magnetic Quadrupole Triplet Focusing IH-DTL [1] and Spatially Periodic RF Quadrupole Focusing (RFQ-DTL) [2]. The first one can has some problems for heavy ions and the second one is complicated at design and tuning.

The Hybrid-RFQ (HRFQ) was proposed in [3] basing on these observations. They used "triplet" mode of RFQ in contrast to IH-DTL using "short lens" mode. It allows to extend the focusing period length and put inside it more drift tubes. The same concept was applied in [1] with magnetic quadrupole triplets.

We propose to choose the RFQ mode due to appointed requirements.

LATTICE CONFIGURATION

The idea is based on the several approaches [4]:

- The transverse acceptance of quadrupole lattice falls as $1/n$ if the focusing period increases.
- Focusing gradient G falls as $1/n^2$ with fixed strength of the lattice.

Here n is the number of "one-sign" lenses in the lattice.

Some variants of static quadrupole lattices are illustrated in Figure 1 [4], where L_F – focusing period.

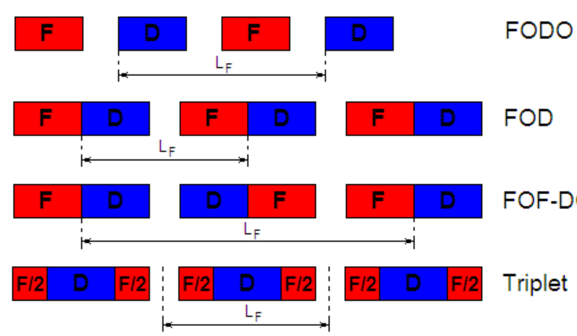

Figure 1: Some variants of static quadrupole lattices.

FOD and Triplet lattices have the shortest period length (on the approach that the lengths of "one-sign" lenses are the same), FODO lattice allows putting twice more drift tubes between lenses with acceptance falling. FOF-DOD lattice has one of the lowest acceptances, but it allows reducing of the focusing gradient to four times. It means that we can use twice bigger aperture to compensate the acceptance reducing.

RF Quadrupole Lenses Design

We can use the static approach for description of the RF quadrupole lens (at single, doublet or triplet mode) in three cases:

- the spatial period of phase oscillations is much longer then focusing period. The parameters of "effective static lenses" are drifting slowly according to current phase of particle in this case.
- RF quadrupole lenses have low "phase dispersion". Limit points of the phase volume will be indefinite in this case.
- the beam phase size of is quite small.

For example, the first case happens in a short FODO structure [2]. The third case is very rare for medium energy beams.

To choose the correct mode of RF quadrupole lens, we should to define the effect of initial phase (phase of RF field, at which the particle enters into lens, counted from the field maximum). It requires solving of the particle transverse motion equation inside the homogeneous RF quadrupole with gradient G:

$$\frac{d^2\rho}{d\xi^2} - \hat{G}\rho\cos\left(\xi/\beta_z + \varphi_{in}\right) = 0,$$
$$\hat{G} = \frac{1}{\beta_z^2}\frac{q}{W_0}\left(\frac{\lambda}{2\pi}\right)^2 G. \quad (1)$$

Here $\rho = 2\pi x/\lambda$, $\xi = 2\pi z/\lambda$ - transverse and longitudinal dimensionless coordinates, $\beta_z = v_z/c$ - longitudinal dimensionless velocity, q and W_0 - charge and rest energy of the particle, $\lambda = c/f$ - wavelength of RF field, φ_{in} - initial phase. Equation (1) is a Mathieu equation. Analytic solving of Mathieu equation is too difficult but we can get some partial solutions by numerical methods. To simplify the problem we can assume that $\Delta\rho/\rho < 1$, $\Delta\rho = \rho|_{out} - \rho|_{in}$. This condition happens in the most number of periodic quadrupole lattices due to requirement of motion stability. Thus some dependence of divergence is changing to $\Delta x' = \Delta(\beta_x/\beta_z) = x'|_{out} - x'|_{in} = x'|_{out}$ (at $x'|_{in} = 0$) versus φ_{in} and the length of RF quadrupole lens has been founded, (see Fig. 2). Curves are calculated for lengths 0.05$\beta_z\lambda$ (curve 1), 0.2 $\beta_z\lambda$ (curve 2), 0.5 $\beta_z\lambda$ (curve 3), 0.93 $\beta_z\lambda$ (curve 4), 1.0 $\beta_z\lambda$ (curve 5), 1.2 $\beta_z\lambda$ (curve 6).

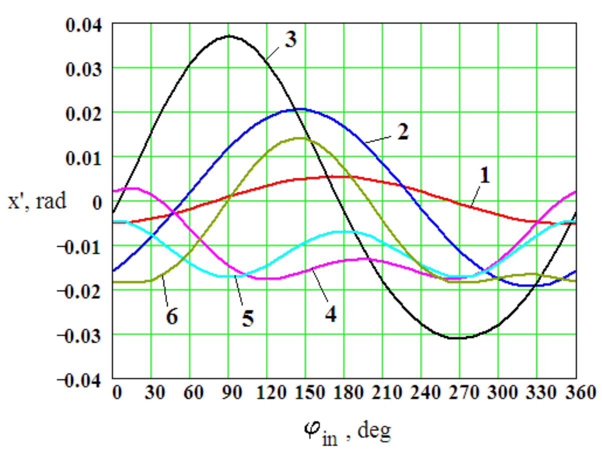

Figure 2: Effect of initial phase and lens length to the transverse motion.

Let us assume to define the effective focusing range at half-height of curve. Curve 2 describes a "short lens": focusing range is 120° and minimal *x'* is -20 mrad. Curve 3 describes a "half-βλ lens": focusing range is 135° and minimal *x'* is -30 mrad. Curve 4 describes a "short βλ lens": focusing range is 248° and minimal *x'* is -17 mrad. Curve 5 describes a "βλ lens" which is unuseful because it has lower strength and higher phase dispersion then "short βλ lens". Curve 6 describes a "1.2 βλ lens" which has the same strength as "short βλ lens" and focusing range is 200° and low phase dispersion.

The effect of reduction of phase dispersion appears with $\Delta\rho/\rho \approx 1$ and the lengths about 0.8 $\beta_z\lambda$ and the gain maximum at 1.5 $\beta_z\lambda$. The RF quadrupole lens works in mixed "doublet-triplet" mode according to initial phase with lens length about $\beta_z\lambda$.

NUMERICAL SIMULATION OF BEAM DYNAMICS

The numerical simulation of the proton beam dynamics in DTL with RF quadrupole focusing was carried out. The space charge influence to the beam dynamics doesn't takes into account to simplify the simulation. Main parameters of the linac are represented in Table 1.

Trajectories of beam particles are shown in Figure 3.

Table 1: Main Parameters of the Linac

Parameter	Value
Energy range, MeV	0.85 – 5.0
Frequency, MHz	150
Gap voltage, kV	150
Focusing gradient, kV/cm^2	135
Linac length, m	1.765
Synchronous phase, deg	30
Aperture radius of RF quadrupole, mm	10.54
RF quadrupole lens length, βλ	0.98
Type of lattice	FOD
Number of accelerating gaps per focusing period	4

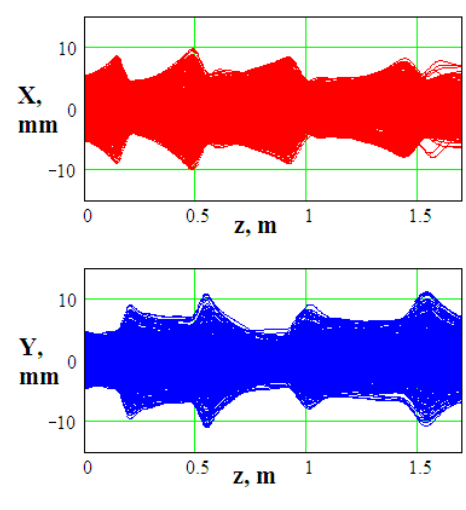

Figure 3: Trajectories of beam particles.

The longitudinal and transverse beam phase spaces are shown in Figure 4 at input (red) and output (blue) of the linac. The main parameters of the beam are shown in Table 2.

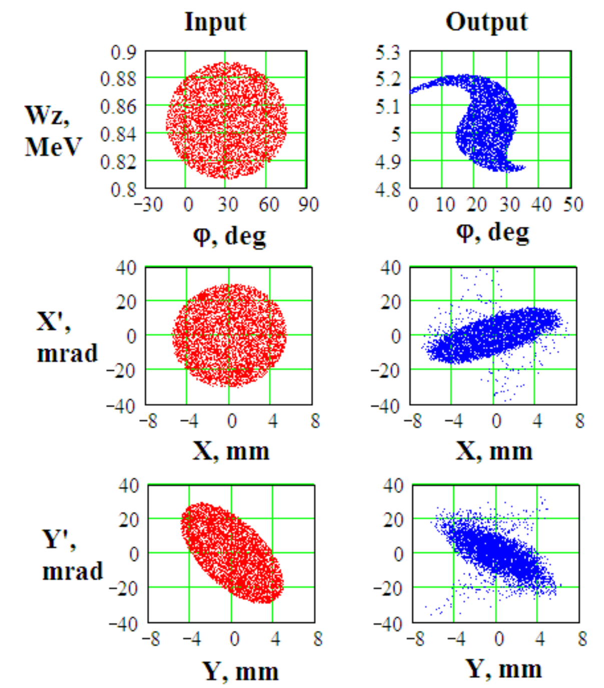

Figure 4: The longitudinal and transverse phase spaces of beam at input (red) and output (blue) of the linac.

Table 2: Main Parameters of the Beam

Parameter	Input	Output
Energy, MeV	0.85	5.0
Energy spread, %	± 5	± 3.4
Phase length of bunch, deg	90	18
X / Y size, mm	5.5 / 4.9	6.9 / 5.7
X' / Y' divergence, mrad	29.8 / 29.0	15.4 / 20.0
E_X / E_Y normalized RMS emittance, π mm mrad	0.75 / 0.50	0.91 / 0.88

CAVITY DESIGN

The RF model of the IH-resonator with RF quadrupoles was proposed (see Fig. 5). It consists of DTL and quadrupole sections which are constructed from 4 βλ rods alternately fixed inside of two rings to generate quadrupole field. Several parameters of the resonator are represented in Table 3.

CONCLUSION

The DTL with RF quadrupole focusing was considered. The different focusing lattices were proposed and discussed. The parameters of RF quadrupole lenses were determined. The most useful operation mode of RF lenses is “doublet-triplet” mode. It can be realized by βλ lenses. The beam dynamics simulation was carried out through the linac. The main parameters of the linac were determined. The beam dynamics simulation confirms the possibility of acceptable focusing by RF quadrupole lenses. But it`s necessary to take into account the space charge influence to the beam dynamics, boundary fields in quadrupoles and to study more variants of lattice for protons and heavy ions future. The RF model design providing combination of DTL and RFQ was proposed.

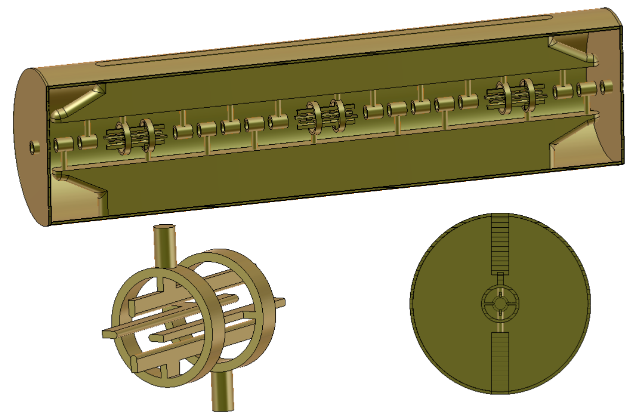

Figure 5: Schematic 3D – model of the IH – resonator with RF quadrupoles.

Table 3: Resonator Parameters

Parameter	Value
Frequency, MHz	150
Tank diameter, m	0.3
Tank length, m	1.2
β	0.05
Q_0	7695
Effective shunt impedance, MOhm/m	19.0
Types of lattice	FOD, FOFDOD

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